DESIGNING AND CONSTRUCTING A MAGNETIC STIMULATOR:

THEORETICAL AND PRACTICAL CONSIDERATIONS

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DESIGNING AND CONSTRUCTING A MAGNETIC STIMULATOR: THEORETICAL AND PRACTICAL CONSIDERATIONS

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Abstract - **Magnetic nerve stimulation has proven to be an effective non-invasive technique that can be used to excite peripheral and central nervous systems. In this technique, the excitement of the neural tissue depends on exposing the body to a transient magnetic field. This field can be generated by passing a high pulse of current through a coil over a short period of time.**

This paper presents general guidelines for designing and constructing a magnetic stimulator. These guidelines cover theoretical concepts, hardware aspects and components required to build these systems. The critical points discussed in this paper are based on key findings and difficulties encountered during the process of building the system used for this study. Furthermore, some suggestions were addressed to improve future designs.
***Keywords* - magnetic nerve stimulation, stimulating system design, stimulating waveforms.**

I. SYSTEM DESIGN: GENERAL CONSIDERATIONS

In previous work we proposed two types of stimulating coils with the objective of improving the coil performance [1].
To evaluate and compare the proposed coils with Figure-8 coils (the type commonly used in clinical and experimental applications) a magnetic stimulator system was built.

Magnetic stimulators employ two major components: a pulse generator and a stimulating coil that couples the energy from the pulse generator to the target nerve via a magnetic field. A typical stimulating circuit is a combination of a switching circuit and a capacitor bank. The capacitor is charged from a power supply with high voltage and then its energy is discharged into the stimulating coil [2,3]. Fig. 1 shows a simple diagram for a stimulating circuit where (L) represents the inductance of the stimulating coil, (R) is the total resistance of the discharge circuit, and (C) is the capacitance of the capacitor bank.

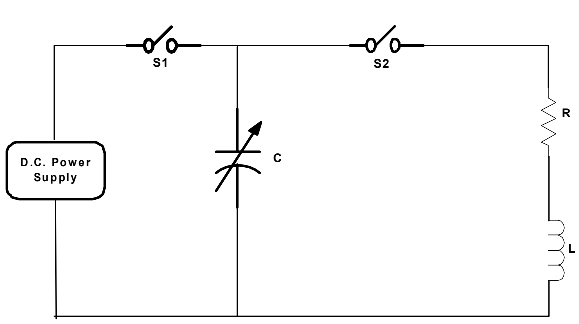

Fig. 1. A simple equivalent circuit of the magnetic stimulator system.

Of the three components, the coil inductance (L) can not be changed as its value is predetermined by the coil design. The value of the coil inductance determines the peak value of the pulsing current as well as the amount of energy stored within the coil. An extremely large inductance reduces the coil current which results in an insufficient induced current within the nerve. On the other hand, an extremely small inductance (despite the high pulsing current passing through it) will not stimulate a nerve as its stored energy is inefficient for triggering [4]. Therefore, when designing a magnetic stimulator, careful selection of the coil inductance is critical in order to achieve the required level of stimulation. Typical values of commercial coils range between 10 and 30 FH.

The circuit equivalent resistance (R) should be maintained at a low value in order for the circuit to generate the desired output (high pulsing current) while maintaining minimum losses. Nevertheless, in some designs, an external resistance can be added to the discharging circuit in order to achieve a monophasic waveform. The alternative to adding the resistor is to increase the value of the charging capacitor. Due to the weight, size, and cost of these capacitors, it is obvious that adding a resistor to the circuit is more practical. This becomes evident considering that a monophasic stimulus is mainly used for single-pulse investigation (low losses) and is rarely used for repetitive stimulation (high losses). Typical values of (R) range between 0.1 and 0.2 S.

The charging capacitor (C) is a pulse charge-discharge type capacitor that is specially designed for such applications and is relatively expensive when compared to equivalent ratings of DC or AC capacitors. This capacitor represents the main parameter that can be used to control the circuit current. If the capacitor value is increased, then the pulsing frequency will decrease. This decreases the rate of flux change in the stimulating coil to a point where it may not be able to excite the nerve. Conversely, decreasing the capacitor value increases the pulsing frequency to a point where the excitation field is faster than the time needed by the neuron to be triggered. In other words, the current rate of change (frequency) is bounded by the nerve depolarization time (for peripheral nerve it is between 0.1 and 0.5 msec)[5]. Accordingly, the circuit frequency ranges between 2 and 10 kHz.

Equation (1) can be used to calculate the (approximate) value of the capacitor required for the stimulating system (assuming the equivalent circuit resistance (R) is small):

$$C = \frac{1}{L(2\pi f)^2} \qquad (1)$$

where f represents circuit pulsing frequency
L represents coil inductance
C represents circuit charging capacitance

Typical values for the capacitor (*C*) (considering both waveforms: monophasic and biphasic) range between 50 and 400 μF, with a maximum voltage of 3 kV [6].

II. MAGNETIC STIMULATOR: HIGH CURRENT PULSE GENERATOR

The main parameters that define the current pulse generated by magnetic stimulators are: pulse type, peak value, duty cycle, rise and fall times, and rate of repetition. Considering all these parameters, the ultimate objective is to have a pulse with a rate of change adequate to excite the targeted nerve. Typical effective rates of change range between 30 and 100 A/μsec [7].

Fig. 2 shows a block diagram that represents the different stages within a magnetic stimulator system. These stages can be grouped into the following clusters:

A. Input stage

This stage provides the system with: rectification, filtering, conditioning, and protection. The output of this stage is typically a DC voltage which supplies the inverter stage. Also, the input stage supplies the power required for the control circuits. A typical input voltage for this stage is 120-240 V while its DC output ranges between a low level of 5-15 V for circuit biasing, and a high level of 200-400 V for charging the main capacitor.

B. Inverter stage

The inverter stage converts the DC voltage (provided by the input stage) to a high frequency AC voltage. The reason for switching to high frequency is to reduce the size of the storage capacitors and the HV transformer which are supplied by this stage. The high frequency ranges from 25-100 kHz. Accordingly, MOSFETs are recommended for this stage due to their high switching capabilities.

C. Step-up voltage stage

The function of this stage is to step-up the voltage using high frequency power transformers. This type of transformer requires more care during the fabrication process compared to conventional transformers. For instance, in addition to the typical parameters that must be considered (volts/turn ratings, layer to layer insulating ratings, type of insulating material, and thermal dissipation), careful attention should be paid to leakage flux, winding geometry, and parasitic leakage capacitance. These constraints are the result of using high frequency.
Furthermore, due to the high frequency, the core of the

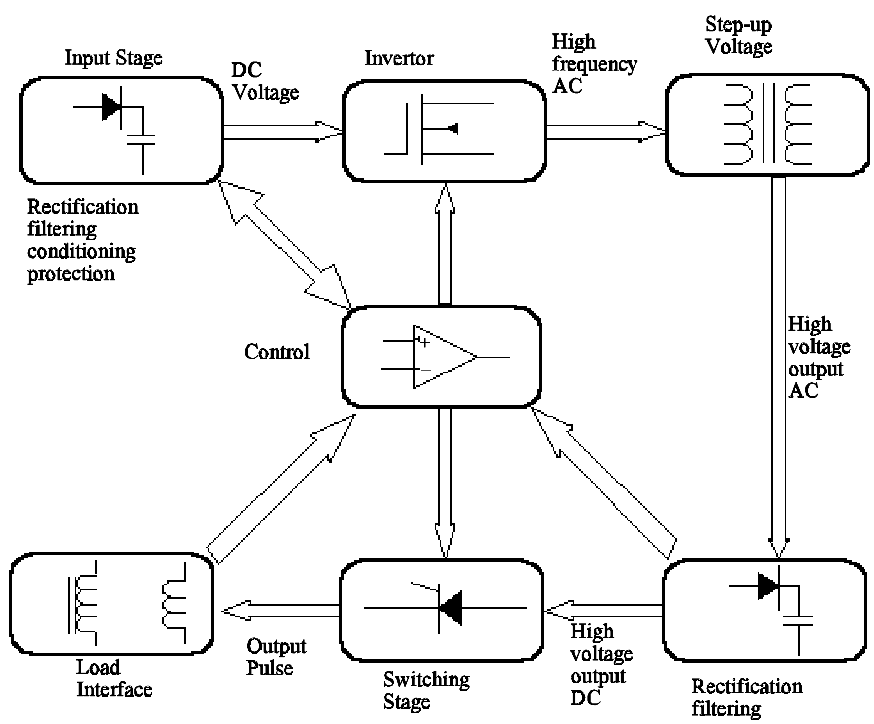

Fig. 2. A Block Diagram of the different stages in a magnetic stimulator.

transformer should be made of a ferrite material. The turns ratio of the transformer depends on the input voltage and the required output voltage. Turns ratios range between 1:5 and 1:10.

D. High voltage stage

This stage is responsible for rectifying and filtering the high frequency AC signal supplied by the step-up transformer. The output of this stage (DC voltage) is used to charge the system main capacitor. In order to maintain the voltage of the main capacitor according to the required level of stimulation, this stage provides feedback to the control stage. In other words, this stage monitors the voltage of the main capacitor and sends this value to the control stage. The control stage will compare it to the reference level (set by the user) and charge or discharge the capacitor.

The rectification and filtering process in this stage utilizes high voltage fast recovery diodes and capacitors. It is crucial to use these types of diodes in this stage in order to provide the system with fast switching capability. All the components in this stage should be isolated from ground level by 8 kV to prevent any voltage breakdown (arcing).

E. High voltage switching circuit

The main function of this stage is to switch the DC voltage stored in the main capacitor and deliver it to the stimulating coil. It is imperative that high insulating, isolating and shielding (electrically and physically) are maintained at all times in this stage. For practical purposes an SCR is an excellent choice to obtain the required pulses [8]. The key points when selecting an SCR are: the rated peak reverse voltage must be at least double the voltage stored across the capacitor, and the maximum searching current must be 10 kAmps or higher. Thermal considerations and heat dissipation should also be considered when constructing this stage. The switching of the SCR can be achieved by using a pulse transformer. The isolation of this transformer should be rated at 8 kV or higher to ensure complete isolation between this stage and the trigger source (the control stage).

F. Load interface

This stage represents the interface between the stimulator system and the coil. Also, this stage provides feedback and monitoring signals (coil temperature and connection) which are usually processed by the control circuit. All of the components in this stage are typically insulated from the ground level.

To monitor the coil temperature a small thermistor is usually embedded in the coil assembly. The signal generated by this thermistor is used to drive an indicator (LCD). If the coil temperature exceeds the maximum rated value the indicator will issue a warning. Also, in the event of losing the voltage (provided by the thermistor) due to a faulty circuit, the control circuit will monitor the voltage level and indicate that an error has occurred in that stage. With regard to the coil connection, a micro-switch can be used. If the coil is not connected properly to the system, a warning will be issued by the control stage.

G. Control stage

The control stage represents the link to all the stages. The basic requirement every control circuit must meet is to precisely regulate the system output to the required level of stimulation. This can be achieved through feedback loops that monitor the output voltage and current then compare them to the desired (reference) output. The difference (error) between the feedback and the reference will cause a change in the control stage that results in a change of power delivered to the load. In a magnetic stimulator, the control stage handles all the monitoring, decision and displaying aspects of the system. This includes the level and the timing required for the pulse, the pulse shape, and the rate of repetition. The control circuitry can range from a few ICs to a microprocessor controlling and monitoring all aspects of the system. Fig. 3 shows the system that was constructed for this study. Fig. 4 shows the switching stage and the capacitor bank.

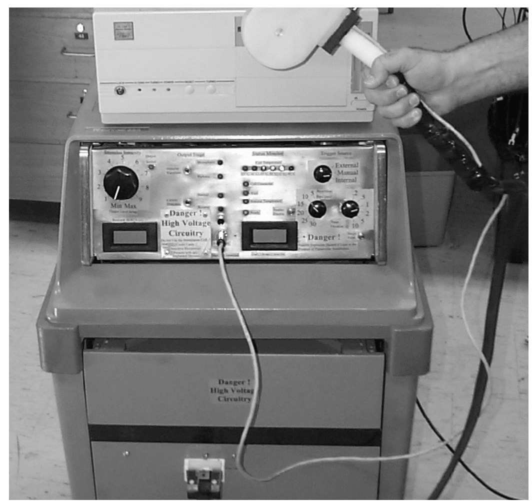

Fig. 3. Magnetic Stimulator System.

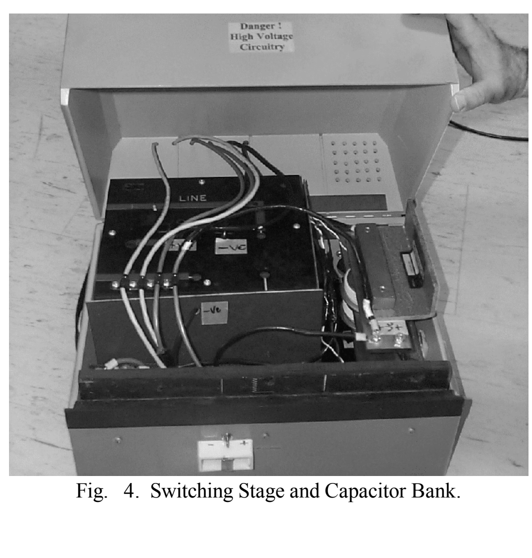

Fig. 4. Switching Stage and Capacitor Bank.

III. CRITICAL ISSUES

1) The key challenge in achieving a reliable control for a magnetic stimulator is to prevent noise from interfering with the signals handled by the control stage. The sources of noise are due to the high ***dI/dt*** and ***dV/dt*** created during switching. The best approach to reduce the noise is to have a resonant switching topology. This can be achieved by adding inductors to the input of the stages that handle high power signals. Furthermore, to prevent the noise from affecting the logic circuitry good shielding practices and a low ripple on the bias voltage are essential.

2) Another critical issue that must be considered is isolation. There are many feedback circuits utilized by this system such as current and potential transformers, shunt and voltage divider resistors. Regardless of the type of circuit used for feedback, it is important to maintain high isolation between the high and low voltages. For the system discussed in this paper, isolating transformers and opto-couplers were implemented. This ensured a safe operating system and proper protection in case of fault.

3) The main criterion of a stimulator is to create a pulse with adequate energy to excite the targeted nerve. This should be applicable for both singular and repetitive stimulation. However, with repetitive stimulation heat build up occurs in the system components, therefore, proper cooling is essential for the system to dissipate the heat [9]. The cooling process can be achieved using heat sinks in conjunction with forced air (fans).

4) The control circuit provides the time period for the pulse duration and the rate of stimulation. The main limitation of increasing the rate of stimulation is the build up of heat in the coil. This build up occurs so quickly that it requires using more than one coil per session. One solution to this problem is to use an external cooling system to aid in thermal dissipation [9].

5) In addition to the issues addressed above, cost and reliability are other items that should be considered when building these systems.

IV. SYSTEM SAFETY

Patient and operator safety is the primary concern when using magnetic stimulation because of the high energy transferred by the system. In particular, the main concern is coil failure because of the coil proximity to both the patient and the operator. Therefore, when designing these types of systems special attention needs to be given to electrical hazards (coil malfunctioning).

Special attention must be given to patients with any implants (pacemaker, metal pins) as unexpected responses may occur [7]. In addition to the above, hardware safety is crucial to prevent any damage that might occur and to maintain system longevity.

V. SUGGESTIONS FOR FUTURE DESIGNS

This paper has briefly discussed the design and practical issues related to magnetic stimulators. To improve future designs, the following suggestions may be considered.
1) Using a capacitor bank with variable values. This will allow controlling the waveform shape and stored energy.
2) Using a micro controller in the control stage to handle most of the tasks through software instead of hardware. This translates to a flexible system that is easy to upgrade.
3) Interfacing a computer with the system for system diagnosing, and maintaining a data base for the patients.
Some of the suggestions listed above have already been implemented in our system.

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